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Exploring synergies and tradeoffs: Energy, water, and economic implications of water reuse in rice-based irrigation systems

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HIGHLIGHTS

- Quantify water, energy and economic implications of water reuse at system level.
- There is a tradeoff between yield and energy use at all different spatial scales.
- Water productivity with water reuse was always higher than without water reuse.
- The cost-benefit ratio shows rice is profitable with and without water reuse.
- Economic benefits of water reuse were lower than from surface water.

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ABSTRACT

Efficient use of water and energy resources are significant requirements for increasing irrigated rice productivity. However, the ever increasingly complex interplay between energy, water and agriculture in feeding both machinery and people, respectively, plus the added impact on and of climate change, have significant implications on the management of our natural resources. This paper holistically analysed a rice-dominated gravity-fed irrigation system using the Upper Pumpanga River Integrated Irrigation System (UPRIIS) in Central Luzon, the Philippines as demonstration example to quantify the water, energy and economic implications of water reuse at five different spatial scales. Water reuse was determined through daily measurements of all surface water inflows and outflows, rainfall, evapotranspiration, and the quantities of water internally reused through check dams and shallow pumping, and aggregated into seasonal totals for five spatial scales during the dry season of 2001. Energy auditing was later used to evaluate the energy implications of water reuse.

Results show that ~30% of the total surface water applied was reused by internal check dams and pumping from shallow groundwater. Across the five spatial scales, water productivity with water reuse was always higher than without water reuse, which reflects the significance of water reuse. The cost-benefit ratio indicates enhanced rice profitability at all five spatial scales with and without water reuse. However, economic benefits of water reuse were lower than economic benefits from surface water, which was mainly due to the higher costs of pumping. Irrigation requires a significant expenditure of fossil energy both for pumping and delivering water to crops. Total energy inputs of water reuse were 28% higher than the energy inputs without water reuse, which was mainly attributed to higher diesel energy inputs.

Whilst water reuse contributes significantly to water productivity across the five spatial scales, it does increase energy use due to pumping. Our holistic analysis indicated a tradeoff between yield and energy use. Achieving higher water productivity would require additional use of fossil energy, which in turn could increase the energy use competition and decrease economic returns. Given the increasing global concerns about climate change and sustainable energy use, an optimal combination of water and energy use is absolutely essential.

1. Introduction

Rice is not only the Earth's staple food, but also constitutes major economic activity and is a key source of employment and in-

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come for many rural communities. Some 75% of the world's annual rice production is harvested from 79 million ha of irrigated lowland rice, mainly in Asia, where it accounts for 40–46% of the net irrigated area of all crops [1]. After the Green Revolution (refers to a series of research, development, and technology transfer initiatives, occurring between the 1940s and the late 1970s, that increased agriculture production worldwide, particularly in the developing world) in the 1960s, the combination of new high yielding rice varieties coupled with increased use of inputs such as water, fertiliser, and biocides, has dramatically increased the productivity of rice [2], and associated profitability contributing to enhanced food security and poverty reduction among farmers with irrigated land [3].

Rice is mostly grown under flooded or submerged conditions and is also one of the largest users of the world's developed freshwater resources [4]. Bouman et al. [5] estimated that 34–43% of the world's irrigation water is used for rice production, because the rice water productivity, i.e. rice production per volume of irrigation water, is very low [6].

However, the sustainability of rice production is under threat largely due to its heavy reliance on water supply and increasing water scarcity, malfunctioning of irrigation systems, and increased competition for water from other sectors [7]. The existing strong interdependence between water use in the rice production and the operation of the irrigation facilities for water services, elicits the need for improving the performance of rice production systems [8]. Rijsberman [7] advocates that the 'soft path' to address the water scarcity problem is to improve the water productivity (WP).

Increasing WP not only requires improved water management practices and the conversion of gravity-fed irrigation systems to pressurised systems, but also upon heavy use of other production inputs such as fertilisers, pesticides, and energy-intensive machinery. However, modern production practices, characterised by the heavy use of such production inputs, have led to a dramatic increase in demand for fossil energy [9,10], raising concerns about the sustainable use of energy resources. Pimentel et al. [11–14], Naylor [15] and Deike et al. [9] have warned that dependence on fossil-fuel inputs is potentially a very serious threat to the growth and stability of world food production. In both developed and developing countries, the energy sector faces a number of environmental and economic issues that have been the subject of increasing government policy interventions. These issues include the long-term depletion of fossil fuels, the increased competing demands for water from industry, agriculture and the environment, increasing fossil fuel prices, declining urban air quality and concerns over global warming due to greenhouse gas emissions [16].

Increased water competition together with the related increasing costs for securing water availability such as high costs of groundwater pumping due to high fossil fuel prices, coupled with the rising costs of modern agricultural inputs are all impacting upon a farmer's income [12]. For example, delivering the 10 ml of irrigation water needed by 1 hectare of irrigated corn from surface water sources requires the expenditure of about 880 kW h/ha generated from fossil fuel [17]. In contrast, when irrigation water is pumped from a depth of 100 m, the energy cost increases sharply to 28,500 kW h/ha, or more than 32 times the cost of surface water [18]. Hodges et al. [19] estimated that 15% of the annual total energy expended for all crop production is used to pump irrigation water. Singh et al. [20] found that in an arid zone in India, irrigation always consumed the most on-farm energy. They suggested that the energy intensity of various crops should be considered in order to determine the most appropriate crops for a given production system.

Irrigated field rice receives 2–3 times more water than other cereals making rice cultivation to a major target for the development of water-saving irrigation technologies [6]. Seasonal water requirements for rice vary widely from as little as 400 mm in heavy clay soils with shallow groundwater tables to more than 2000 mm in coarse textured soils with deep groundwater tables [22,23] with 25–85% of all water inputs into rice fields succumbing to percolation [20,21,22,23]. Though percolations are deemed losses at the field level, they can be captured and reused downstream and do not necessarily lead to true water depletion at the irrigation system level. Therefore, it has been argued that the efficiency of water use and the water productivity of rice may increase with increasing spatial scale and may be much higher at the irrigation system level than at the individual field level [6]. However, the recapture and reuse of water that is "lost" upstream involves additional investment and operation costs, such as pumping or the building of dams downstream [24]. Consequently, it is important to determine the economic and energy implications while considering the water reuse options for improving the water productivity at the system level.

In a low-carbon water-constrained future, new challenges for irrigated agriculture is to continue to increase production under intensifying water and energy conflicts. In particular, rise in water scarcity, need to reduce reliance on fossil fuels, and increase in energy demand and associated energy costs would present great water–energy management challenges over the coming decades [25,26]. Therefore, efficient uses of water and energy resources are vital for increasing the production, productivity, and competitiveness of agriculture, as well as maintaining environmental values and longer-term environmental sustainability. However, the increased use of water and energy inputs has an impact on climate change and upon the sustainability of our natural resources management. Therefore, the need to increase rice water productivity whilst reducing dependency on energy resources, demands a detailed understanding of water and energy use patterns in high-input farming systems [27].

In this paper, we quantify the productivity of water, energy and the economic implications of water with and without reuse in a rice-dominated surface irrigation system in the Philippines. We estimated water reuse through actual water flow measurements and pumping surveys. Using the water accounting principles of Molden [28], we calculated water productivity with and without the reuse of water at the irrigation system level. Using data from the pumping survey, allowed the estimation of the costs of pumping (based on 2001 values of US$), energy usage and the economics of pumping and water reuse at the system level.

2. Materials and methods

2.1. Study area

The study area was District I of the 102,000 ha Upper Pampanga River Integrated Irrigation System (UPRIIS) in Central Luzon, Philippines (Fig. 1). The UPRIIS is owned and operated by the National Irrigation Administration (NIA) of the Philippines. It has the main purpose of providing irrigation water to rice fields producing an average of 63 million tons of rice every year. District I has a total area of 28,205 ha including rice fields (dominant land use), upland crops, vegetables, roads, settlements, and surface water water bodies. The District I is bounded by the Talavera River to the east and the Ilog Baliwag River in the west, and consists of an upper part, called the Talavera River Irrigation System-Lower (TRISL), and a lower part called the Santo Domingo Area (SDA). Water is supplied to District I by both Diversion Canal 1, which receives its water from the Pantabangan reservoir, and the TRIS main canal which gets its water from the Talavera River through a run-off-the-river diversion dam. The major direction of water flow is from northeast to southwest. The TRIS main canal first supplies water